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Final Report
to the
National Aeronautics and Space Administration

"THE PROPAGATION AND ATTENUATION OF COMPLEX ACOUSTIC WAVES IN
TREATED CIRCULAR AND ANNULAR DUCTS"

(NASA-CR-146814) THE PROPAGATION AND
ATTENUATION OF COMPLEX ACOUSTIC WAVES IN
TREATED CIRCULAR AND ANNULAR DUCTS Final
Report, 5 Dec. 1974 - 29 Feb. 1976
(Pennsylvania State Univ.) 18 p HC \$3.50

N76-21371

Unclas
G3/32 25170

Research Grant #NSG 1126

Grant Period: December 5, 1974 - February 29, 1976

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ABSTRACT

The propagation of plane waves and higher order acoustic modes in a circular multisectioned duct has been studied. A unique source array consisting of two concentric rings of sources, providing phase and amplitude control in the radial, as well as circumferential direction, was developed to generate plane waves and both spinning and non-spinning higher order modes. Measurements of attenuation and radial mode shapes were taken with finite length liners inserted between the hard wall sections of an anechoically terminated duct. Materials tested as liners included a glass fiber material and both sintered fiber metals and perforated sheet metals with a honeycomb backing. The fundamental acoustic properties of these materials were studied with emphasis on the attenuation of sound by the liners and the determination of local versus extended reaction behavior for the boundary condition. A search technique has been developed to find the complex eigenvalues for a liner under the assumption of a locally reacting boundary condition.

The experimental results were compared with a mathematical model for the multisectioned duct which includes the modal transmission and reflection effects at the interface between sections with different liner admittance. The good agreement between measurement and theory indicates that the multisectioned duct analysis can be used to predict the sound field in a complicated system of several different liner sections.

Furthermore, the local reaction boundary condition is valid for the sintered fiber metal and perforated panel liners but can only be used in cases of moderate sound attenuation for the glass fiber material. For each of the acoustic modes studied, the sound attenuation characteristics of the fiber metal materials were significantly better than those for the perforated panels.

The NASA Technical Officer for the research program was Dr. Joe W. Posey of the Langley Research Center.

INTRODUCTION

Although not a new topic, the subject of duct acoustics has become an area of renewed interest. This interest has been generated as a result of current jet engine noise reduction programs. A large portion of these programs have been oriented towards the application of acoustic treatment to jet engine inlet ducts. Additional interest in duct acoustics has been motivated by the need to suppress noise in air conditioning ducts and large air moving systems.

A typical solution to the reduction of noise from a duct system is to insert an acoustically absorbent liner material in the duct. This material attenuates the sound before it is radiated from the duct outlet. However, acoustic propagation in the duct and attenuation by the liner are complicated by several factors, including the modal content of the sound, the acoustic properties of the material, the finite length of the liner, the termination of the duct, and the presence of flow. The effect of each of these will be briefly discussed.

Much of the initial work in duct acoustics concentrated on the propagation and attenuation of plane waves. Studies to evaluate liner performance were concerned with assigning a single number rating to a material to describe its attenuation per unit length for the plane wave mode. However, this is not the only mode present within the duct. It has been shown that axial flow compressors and turbines generate higher order acoustic waves of a spiralling nature in a duct. Therefore, the importance of considering the attenuation of these higher order modes when evaluating liner performance must be emphasized.

Test methods for evaluating liner performance often do not yield significant information on attenuation by individual modes. As an example, a common test method measures the attenuation of sound through a lined duct section connected to a broad band noise at one end and to an anechoic or reverberant chamber at the other end. The insertion loss of the liner can be determined by measuring the sound attenuation as a function of frequency. However, the broad band noise source obscures the effects of higher order modes and this method can only yield comparative information on the sound attenuation characteristics of liners.

The acoustic properties of a duct lining material are specified by a normal impedance which determines the modal attenuation of sound through the duct. In certain cases, this impedance can be optimized to produce maximum attenuation but this result is difficult to achieve over a broad frequency range or for more than one mode.

When a finite length liner is inserted in a duct, the impedance discontinuity between the surface of the duct and the surface of the liner causes reflection of an incident wave. This introduces a standing wave in front of the liner. Furthermore, reflection from the termination plane of the duct must also be considered as it too will cause a standing wave.

The presence of uniform mean flow within a lined duct will modify the attenuation of the liner. In general terms, the attenuation of a lined duct increases for acoustic propagation against the direction of flow and decreases for propagation with the direction of flow.

The sound attenuation of individual liners can vary significantly with airflow velocity. As the airflow velocity is varied, the peak

attenuation varies in a manner which is dependent upon the change in acoustic properties of the liner. The effect of flow on locally reacting liners is to increase the acoustic resistance of the liners at low frequencies. Flow effects on reactance are less significant but tend to increase the reactance of the liner with increasing velocity. Thus for maximum benefits of sound attenuation, it is necessary to design lining treatment for the flow velocity region and acoustic environment in the duct in which it will be used.

Each of these factors will have an effect on the attenuation of sound in a lined duct. However, each effect must be understood separately before the combination of these effects may be studied. In a final analysis, the individual effects may be combined to simulate the environment of an actual jet engine for example.

Recently there has been an interest in acoustic propagation in circular ducts of several different sections. This work was motivated by the physical situation of sound radiating through the successive lined and unlined sections of an aircraft engine inlet duct. Due to the changes in liner impedance for each duct section, the boundary condition also changes and an acoustic wave is partially transmitted and partially reflected at the interface between different sections. Thus, it is possible to take advantage of the reflection effects between sections as well as the transmission effects of the liners to attenuate sound. Lansing and Zorumski (1) have performed a preliminary analysis of acoustic propagation in a multisectioned duct. Their results show that a combination of several different duct liners can perform significantly better than a uniform duct liner. Extensive parametric studies of optimum liner configurations have been performed by Beckemeyer and

Sawdy (2) to maximize sound attenuation for a two dimensional multi-sectioned duct.

Despite the promising analytic work in the area of multisectioned ducts, there is a lack of experimental data to substantiate these studies. Nonetheless, this analysis provides a unique approach, as well as a realistic model, for analyzing sound attenuation in lined duct systems.

The basic objective of this study was to investigate current multi-sectioned duct theory through both experimental and analytical techniques. The propagation of plane waves and higher order acoustic modes was studied in an anechoically terminated circular duct with three sections. Measurements of attenuation and mode shapes were made for a variety of liner materials over the full frequency range at which a mode can be generated. Sound fields necessary for excitation of various modes were generated by a spinning mode synthesizer. This system was capable of generating the spinning modes characteristic of axial flow compressors and provided a means of experimentally studying the propagation and attenuation of higher order duct modes.

In addition, the fundamental properties of sound absorbing liners were studied with emphasis on the attenuation of sound by the liner and the determination of local versus extended reaction behavior.

This work was conducted with no flow. Although high speed flow is present in an actual jet engine, the simple case of a lined duct without flow must be fully understood before progress can be made for the more complicated situation. It is hoped that the effects of flow will be the subject of a future research project.

Topics that were investigated in this study included:

1. The development of a source array capable of generating plane waves and higher order acoustic modes in a hollow circular duct
2. The experimental measurement of plane wave and higher order mode propagation in a multisectioned duct
3. The development of a mathematical model for acoustic propagation in a multisectioned duct
4. The analysis of boundary conditions and attenuation for duct liners of various acoustic materials

The full scope of the analytical and experimental investigations in this research are reported in Dr. B. Wyerman's Ph.D. dissertation (3) which also includes a comprehensive bibliography.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This research program has achieved its goal of understanding the behavior of acoustic propagation in multisectioned ducts. In addition, materials used in the study were evaluated. Developments in both experimental and analytical techniques were achieved as a result of this work and will be described in this section. Furthermore, interesting topics for future research are outlined.

The propagation of plane waves and higher order modes in an infinite hard-walled circular duct was first described. An understanding of this process is necessary for study of more complex cases of acoustic propagation. This effort was then expanded to consider propagation in ducts lined with different acoustic materials.

The fundamental acoustic properties of materials representative of three types of duct liners commonly used in different applications were studied. These included a porous glass fiber material, a sintered fiber metal material with an air cavity backing, and a panel of Helmholtz resonators. Expressions were developed to predict their acoustic characteristics and the normal impedance measured by a standing wave tube was compared with values calculated from theory. In all cases, except for the porous material, there was good agreement between measurement and theory throughout the entire frequency range. This ability to model a liner material and predict its impedance is a valuable tool for designing liners with optimum attenuation properties.

The properties of these materials as duct liners were studied with emphasis on determination of local versus extended reaction boundary conditions. The local reaction boundary condition was valid for the

fiber metal and resonator cavity type material. However, for cases of significant sound attenuation within a duct, the extended reaction boundary condition must be adopted for liners of porous material.

A method using both contour integrations and an iteration technique was developed to find the complex eigenvalues for a liner under the assumption of a local reaction boundary condition. This search technique provided an efficient and reliable means for locating successive eigenvalues in the complex plane for an arbitrary complex admittance.

Once the fundamental properties of acoustic propagation in lined and unlined ducts are understood, these effects may be combined to consider propagation in a duct containing successive lined and unlined sections. Due to the changes in liner impedance for each finite section of the duct, an incident acoustic wave is partially transmitted and partially reflected at the interface between different sections. Using a matrix technique, relationships were developed to account for the acoustic coupling between sections of a hollow circular duct with no flow. The modal amplitudes of the sound field at each interface within the duct are then defined in terms of modal transmission and reflection matrices. For a circular duct with multisection liners, the reflection effects are proportional to the difference in acoustic admittance between adjacent liners. Thus, it is possible to take advantage of the reflection effects between sections as well as the transmission effects of each liner to produce attenuation. Because of this characteristic, a combination of different liners could perform significantly better in attenuating sound than a continuously lined duct. A computer program was developed to model the multisectioned duct based on the admittance and eigenvalues for each section.

A complex source array consisting of two concentric rings of sources was developed to generate plane waves and both spinning and non-spinning higher order modes in a duct. These modes could be generated at their cut-off frequencies and throughout a frequency range extending to the cut-off frequency for the next higher radial mode. Through individual control of the response of each element, the array provided phase and amplitude control in the radial, as well as circumferential, directions. The radial dependence of the measured mode shapes was enhanced considerably by the design of this unique array.

Once it was established that the source array could generate modes with a reasonable degree of purity, the propagation of higher order modes in a multisectioned duct was studied. The duct system consisted of an anechoically terminated duct 12 inches in diameter with 3 sections. Mode shapes generated included the $(0, 0)$ plane wave mode, the $(0, 1)$ non-spinning mode, and the $(1, 1)$ and $(2, 1)$ spinning modes. Measurements of attenuation and radial mode shapes were taken throughout the duct when a finite length liner was inserted between upstream and downstream hard-walled sections. Materials tested as liners included a glass fiber material and both a sintered fiber metal and perforated sheet metal with a honeycomb backing. The experimental measurements were compared with results calculated from the mathematical model of the system. There was generally good agreement between measurement and theory for both non-spinning and spinning modes. The comparison indicates that the multisectioned duct analysis accurately predicts the mode shapes and levels at stations throughout the duct. Furthermore, the local reaction boundary condition is valid for the fiber metal and perforated panel liners. For low to moderate attenuation of sound, this

assumption was valid for the liner of glass fiber material but should be modified in favor of the extended reaction boundary condition for significant attenuation through a duct lined with this material.

Despite the ability of the source array to match the sound field for both the circumferential and radial pressure dependence, the generation of an individual mode is often obscured by contamination from additional spurious modes. These spurious modes are generated as a result of phase variations between individual elements of the array and can include plane waves and circumferential modes in both the clockwise and counterclockwise directions. Although they are very seldom noticed in an unlined duct, their presence is often evident in the downstream section of a lined duct. In this case, the desired mode and each of the spurious modes are attenuated at different rates by the liner. The contribution of these spurious modes was analyzed for various phase differences in the array.

The attenuation characteristics of each of the liner materials was evaluated by the multisectioned duct analysis. For a finite length liner, the acoustic attenuation cannot be specified in terms of an attenuation constant for a particular mode because reflection effects caused by the impedance discontinuity on each side of the liner must be considered. This introduces a standing wave within each section. Therefore, the transmission loss and insertion loss were used to evaluate liner performance for each material. These characteristics were determined as a function of frequency for each mode.

The results indicate that there is greater attenuation for spinning modes than for non-spinning modes for each of the liner materials. Furthermore, spinning modes of high circumferential order are attenuated

more than spinning modes of low circumferential order. There is up to a 16 dB difference between the increased sound attenuation of a plane wave for a 28-1/2" length of fiber metal liner than for a perforated panel liner and over 40 dB difference between the attenuation of the first spinning mode for these same materials.

The superior acoustic performance of the fiber metal liners is explained by the strong reactive component of the impedance while the perforated panel liners are predominantly reactive materials at low frequencies. The characteristics of these materials could be used to advantage in designing segmented liner configurations of resistive and reactive liners. Such a configuration could take advantage of the reflection effects between successive liners of different admittances and could easily be analyzed by the multisectioned duct theory.

A further significance of multisectioned liners is that modal conditioning may occur and result in increased attenuation as its primary effect. Thus, an incident acoustic wave could be redistributed by an initial liner section into modes which are more readily absorbed by the remaining lining segments. These aspects provide interesting topics for future research.

The results of the study suggest several areas of further research in duct acoustics. Of primary importance is the improved liner performance that may be obtained for a segmented duct configuration of several different liners. The multisectioned duct analysis described in this study could easily be extended to consider configurations of several different duct liners. Furthermore, this analysis could be applied to annular or rectangular ducts as well.

A complete parametric study of acoustic propagation in a multi-

sectioned circular duct would provide useful information for optimizing sound attenuation for both spinning and non-spinning modes. Beckemeyer and Sawdy (2) have performed such an analysis for a two dimensional duct. Their results show that the reflection effects at the interface between two different liner sections may not be as significant a factor in improving sound attenuation as the modal conditioning between sections. An optimum two segment liner has been shown to consist of an initial reactive liner followed by a resistive liner. In this case, the acoustic energy within the first section is converted into modes which are more easily attenuated within the resistive section. Similarly, the optimum configuration for a three segment liner consists of a combined reactive - resistive-reactive configuration. It would be interesting to compare these results for a two dimensional duct to similar configurations in a circular duct for both spinning and non-spinning mode. Furthermore, additional liner combinations for a circular duct should be investigated to optimize sound attenuation for various modes.

A limiting factor in such an optimization scheme is the infinite number of possible liner configurations and the resulting computer time involved to analyze these combinations. Arnold (4) has developed a sparse matrix technique applicable to multisectioned duct analysis which greatly reduces computer time. It would be recommended that this technique be implemented for future studies involving extensive computer work. Since the acoustic characteristics of both fiber metal and Helmholtz resonator type materials can be controlled by the material properties, liners with desired impedance characteristics can be designed. Therefore, the results of optimization studies should be used to design more effective sound absorbing duct liners which can be implemented for

experimental studies. These studies should include duct systems of two or more different liner materials for both annular and hollow circular ducts.

Further investigations should include the effects of mean flow and of various flow profiles on the sound attenuation produced by segmented liners. This situation would then provide a more realistic approximation of the acoustic environment in an actual jet engine inlet duct. When flow is considered, the resulting eigenfunctions are shown by Zorumski (3) to be non-orthogonal. Due to the matrix formulation of the problem, this effect, however, would not seriously complicate the analysis. When flow is included, continuity of particle displacement or particle velocity at the liner becomes the governing boundary condition depending on the flow profile. A discussion of the differences between each boundary condition is given by Lansing and Zorumski (1).

Additional experimental work is warranted to study acoustic propagation and sound attenuation in acoustically lined flow ducts. This work would provide confirmation of the proper boundary conditions in the presence of flow. Since the source array developed in the study is placed at the end of the duct, it could not be used with experiments which include flow. Additional techniques for generating higher order modes with reasonable modal purity would need to be developed in this case.

When a length of porous material is used as a duct liner, the boundary condition at the surface must be modified to consider acoustic propagation within the liner as a separate media. This introduces the extended reaction boundary condition. It would be interesting to compare the successive eigenvalues evaluated for this boundary condition with

eigenvalues for the same material evaluated from the local reaction boundary condition. The conversion of energy between successive modes should also be studied for the extended reaction boundary condition. This analysis might provide information on optimum segmented liners consisting of a combination of extended reacting and locally reacting liners.

The acoustic characteristics of glass fiber materials, however, could not be as accurately predicted from the fundamental material properties. Therefore, additional work to describe the acoustic characteristics and dissipation mechanisms of these and other porous material in terms of various physical characteristics should be performed. These results would provide a significant improvement over the phenomenological approach of using a structure factor or effective parameters determined from experimental measurements to explain the attenuation characteristics of these materials.

Although acoustic propagation in an anechoically terminated circular duct of three sections with no flow has been the subject of the study, this analysis may be easily extended to consider several different configurations. The multisectioned duct analysis could be applied to annular and rectangular ducts, as well as to other duct geometries. The matrix formulation used in this analysis permits consideration of several different duct sections without undue complications.

To provide a more realistic approximation of the acoustic environment in an actual jet engine inlet duct, flow may also be included in this analysis. The resulting eigenfunctions are shown by Zorumski (3) to be non-orthogonal. Due to the matrix formulation of the problem,

this effect would not seriously complicate the analysis. When flow is considered, continuity of particle displacement or particle velocity at the liner becomes the governing boundary condition depending on the flow profile. Since the source array developed in this study is placed at the end of the duct, it could not be used with experiments which include flow. Additional techniques for generating higher order modes would need to be developed in this case.

The results of this study suggest that better liner performance may be obtained by extending theoretical and experimental work to explore segmented duct configurations of several different liner materials. Additional areas of experimental study include duct systems of two or more different liner materials for both annular and hollow ducts. Furthermore, since the acoustic characteristics of a material were shown to be controlled by the material properties, liner impedance may be modified through these properties to produce optimum attenuation.

A complete parametric study of acoustic propagation in multi-sectioned ducts would provide useful information for optimizing the attenuation of sound. A limiting factor in such an analysis is the infinite number of possible liner configurations and the resulting computer time involved to analyze these combinations. Arnold (34) has developed a sparse matrix technique applicable to multisectioned duct analysis which greatly reduces computer time. It would be recommended that this technique be implemented for further studies involving extensive computer work.

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- a) Number 1 - January 14, 1975
- b) Number 2 - February 3, 1975
- c) Number 3 - March 3, 1975
- d) Number 4 - July 28, 1975

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DR. B.R. WYERMAN'S PH.D. DISSERTATION

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